Effects of Ozone and Other Pollutants on the Pulmonary Function of Adult Hikers

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This study evaluated the acute effects of ambient ozone (O_3), fine particulate matter ($PM_{2.5}$), and strong aerosol acidity on the pulmonary function of exercising adults. During the summers of 1991 and 1992, volunteers (18–64 years of age) were solicited from hikers on Mt. Washington, New Hampshire. Volunteer nonsmokers with complete covariates (n = 530) had pulmonary function measured before and after their hikes. We calculated each hiker's posthike percentage change in forced expiratory volume in 1 sec (FEV_1), forced vital capacity (FVC), the ratio of these two (FEV_1/FVC), forced expiratory flow between 25 and 75% of FVC ($FEF_{25-75\%}$), and peak expiratory flow rate (PEFR). Average O_3 exposures ranged from 21 to 74 ppb. After adjustment for age, sex, smoking status (former versus never), history of asthma or wheeze, hours hiked, ambient temperature, and other covariates, there was a 2.6% decline in FEV_1 [95% confidence interval (CI), 0.4–4.7; p = 0.02] and a 2.2% decline in FVC (CI, 0.8–3.5; p = 0.003) for each 50 ppb increment in mean O_3. There were consistent associations of decrements in both FVC (0.4% decline; CI, 0.2–0.6, p = 0.001) and PEFR (0.8% decline; CI, 0.01–1.6; p = 0.05) with $PM_{2.5}$ and of decrements in PEFR (0.4% decline; CI, 0.1–0.7; p = 0.02) with strong aerosol acidity across the interquartile range of these exposures. Hikers with asthma or a history of wheeze (n = 40) had fourfold greater responsiveness to ozone than others. With prolonged outdoor exercise, low-level exposures to O_3, $PM_{2.5}$, and strong aerosol acidity were associated with significant effects on pulmonary function among adults. Hikers with a history of asthma or wheeze had significantly greater air pollution-related changes in pulmonary function. *Key words*: aerosol acidity, air pollution, fine particulate matter, ozone, pulmonary function. *Environ Health Perspect* 106:93–99 (1998). [Online 22 January 1998]
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Acute ozone (O_3) exposure is associated with reversible decrements in pulmonary function (*1,2*), and O_3 inhalation can precipitate symptoms of lower respiratory irritation such as cough, shortness of breath, and pain with inspiration (*3,4*). Controlled chamber exposure studies have shown that O_3 is associated with acute declines in lung function and increased respiratory symptoms at exposure levels ranging from 80 to 400 ppb (*2,5*). Far less is known about the response of adults with more diverse demographics and fitness levels who are exposed to low-level O_3 during vigorous exercise in the ambient environment. Furthermore, there are inconsistencies between results of controlled exposure and observational studies regarding the exposure–response relationship and, in particular, whether there are levels of O_3 exposure below which acute health effects are not detectable.

We evaluated the acute effects of ambient O_3 and concomitant fine particulate matter ($PM_{2.5}$) and aerosol acidity exposures on pulmonary function in a diverse population of healthy adults exposed to varying O_3 levels while hiking on Mt. Washington in the White Mountain National Forest of New Hampshire.

Photochemical reactions of nitrogen oxides and hydrocarbons from upwind industrial and urban areas of the central and northeastern United States produce episodically high O_3 levels in the Mt. Washington area. For example, hourly mean O_3 concentrations on the mountain between 1987 and 1993 ranged from 0 to 148 ppb (*6*). The White Mountain National Forest is a popular site for outdoor recreation, with over 7 million visitor days each year, including 60,000 hikers on Mt. Washington and additional hikers on neighboring peaks who are exposed to elevated O_3 while exercising.

Methods

Volunteers were solicited from adults (18–65 years of age) beginning a day hike on Mt. Washington from the trail entrance at Pinkham Notch, New Hampshire, on 78 days during the summers of 1991 and 1992. A study researcher, spirometry equipment, and a sign soliciting volunteers were placed in full view of all hikers who used this trail entrance. All passing hikers who agreed to participate were evaluated. The study researcher and hikers were unaware of the ambient O_3 or other pollutant levels. After explaining the study, the researcher obtained written informed consent from each subject before his/her evaluation. This study was approved by the Human Research Committee of Brigham and Women's Hospital. Only current nonsmoking subjects were included in these analyses.

Spirometry measurements. Pulmonary function was measured outdoors at 620 m above sea level next to the entrance of the main trails to the summit of Mt. Washington. Each participant performed a minimum of three and a maximum of eight forced expiratory maneuvers before the day's hike and again after returning to the base. Prehike tests generally were performed between 0800 and 1030 hours and posthike tests were performed between 1500 and 1930 hours. Most (90%) posthike testing was performed within 25 min of completion of the hike. Subjects were tested, while seated and wearing nose clips, with a 12-liter Morgan Spiroflow spirometer (P.K. Morgan, Andover, MA) attached to a personal computer with customized software. The spirometer was calibrated twice daily with a 3-liter syringe, before the prehike and posthike assessments.

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For each hiker, mean values for forced expiratory volume in 1 sec (FEV_1) and forced vital capacity (FVC) were the means of the two or three best acceptable (*7*) and reproducible (± 5%) values. Values for forced expiratory flow between 25 and 75% of FVC ($FEF_{25-75\%}$) and peak expiratory flow rates (PEFR) were taken from the acceptable and reproducible maneuvers that had the maximum sum of FEV_1 and FVC. All spirometry values were corrected to body temperature and pressure saturated with water (BTPS). Percentage change in pulmonary function was calculated as 100 times the posthike minus prehike pulmonary function divided by the prehike value.

Questionnaire measurements. Each subject was given a diary to complete during the hike and instructed in taking his/her own pulse. The diary included a record of each hiker's location, the time of day when the location was reached, and the hiker's pulse and respiratory symptoms at four points on the hike—beginning, halfway, high point, and finish.

After completion of his/her climb, each participant completed a modified American Thoracic Society-Division of Lung Disease (ATS-DLD) questionnaire (*8*) with questions regarding demographic information, past respiratory illnesses and symptoms, tobacco use, and weekly aerobic exercise. Information on medication use was not obtained.

Environmental exposure measurements. Continuous O_3 measurements were made both at the Mt. Washington Observatory on the summit (1,910 m above sea level) and on the east side of the mountain base near the beginning of the Mt. Washington Auto Road (480 m above sea level). Summit monitoring used a chemiluminescent O_3 analyzer (Model 8410-E Ozone Analyzer; Monitor Labs, San Diego, CA) in 1991 and an ultraviolet photometric O_3 analyzer (Model 1008-RS; Dasibi Environmental Corp., Glendale, CA) in 1992. The base site used an ultraviolet photometric O_3 analyzer (Model 49-100; ThermoEnvironmental Corp., Franklin, MA). At the summit site, external O_3 monitoring performance was audited by the EPA and the state of New Hampshire Air Resources Division. At the base site, internal calibrations were conducted twice monthly. Ambient O_3 concentrations were expressed as the hourly mean of continuous O_3 monitoring. Hiker-specific mean O_3 exposures were defined as the average of both the summit and the base hourly ambient O_3 concentrations over the hours during which the individual hiked.

Fine particulate matter or $PM_{2.5}$ (aerodynamic diameter ≤2.5 μm in micrograms per cubic meter) and strong aerosol acidity (expressed here as sulfuric acid equivalent mass concentration in micrograms per cubic meter) were measured near the base of the mountain. Fine particulate matter was sampled on a Teflon filter with a 10-l/min Harvard Impactor (Air Diagnostics and Engineering, Inc., Harrison, ME) (*9*). Strong aerosol acidity was sampled with a modified Harvard Impactor with an ammonia denuder to minimize acid neutralization (*10*). Fine particulate matter and strong aerosol acidity samplers operated for approximately 10 hr (0800 to 1800 hrs) on most days during which spirometry was performed and results were reported as a single integrated daytime measure. Fine particulate matter and strong aerosol acidity samplers were audited for internal performance approximately halfway through each summer; measurements were corrected to standard temperature and pressure and reviewed for compliance with quality assurance and quality control specifications based on a modification of previously established standards (Harvard 24 City Acid Aerosol Study: Data Processing Procedures; July 1992). On one day of sampling, $PM_{2.5}$ and strong aerosol acidity samples failed to meet these specifications and were excluded from these analyses.

Ambient temperature was measured at the base of the mountain during each hiker's prehike and posthike spirometry. In addition, daily ambient mean temperatures were obtained from National Oceanographic and Atmospheric Administration weather sites on the summit (the Mt. Washington Observatory) and at the Appalachian Mountain Club facility at the base of the mountain.

Hiking (or exposure) time was defined as the difference between the times of the prehike and posthike spirometry tests for each participant.

Statistical methods. Three pollutant exposure variables were considered in these analyses: the average of both the base and summit hourly O_3 concentrations for the hours of each hiker's hike (hiker's mean O_3 per hour of hiking); daily $PM_{2.5}$ concentrations; and daily strong aerosol acidity concentrations. Each hiker's mean O_3 exposure was calculated if hourly base and summit O_3 data were available for at least 50% of the hike. Five outcome variables were studied: the posthike percentage change in each of FEV_1, FVC, FEV_1/FVC, $FEF_{25-75\%}$, and PEFR. The relationship of O_3 to lung function was assessed using five different methods: quintile analysis, nonparametric smoothing, linear regression, piecewise linear regression, and logistic regression. Potential confounders of the relationship between O_3 exposure and acute changes in pulmonary function that were considered as linear terms in the models included ambient temperature (mean daily temperatures at the summit and base of the mountain as well as mean temperatures at the time of prehike and posthike spirometry) and daily $PM_{2.5}$ and strong aerosol acidity concentrations. Other covariates considered as linear terms were age, height, hours hiked, a proxy measure of fitness (average hours of aerobic exercise per week), and proxy measures of hike work [estimated backpack weight, self-reported maximum pulse over the hike, and percentage of age-predicted maximum pulse achieved during the hike (age-predicted maximum pulse was defined as 220 minus age)]; covariates considered as categorical variables were sex, smoking status (former versus never), a history of physician-diagnosed asthma, a history of chronic bronchitis, a history of any wheeze, a history of severe wheeze symptoms (at least two episodes of wheeze associated with shortness-of-breath over the previous year), year of hike, and proxy measures of hike work (carrying a backpack and reaching the summit of Mt. Washington). Covariates that were consistently significant in multivariate models (coefficients with two-sided *t*-tests with $p<0.15$) or that were considered to be of *a priori* importance (ambient temperature, sex, smoking status, history of physician-diagnosed asthma or severe wheeze, and certain proxy measures of hike work) were retained in the final models.

To assess effect modification by categories of respiratory disease history, smoking status, sex, hours hiked, and proxy measures of hike work, a Wald chi-square test for interaction between O_3 and each covariate was used, with hours hiked divided at the median. In addition, age was divided into 10-year age groups to compare the O_3 effect across four age categories (18–27, 28–37, 38-47, ≥48).

Hikers' mean O_3 exposures were divided into quintiles and plotted against the percentage change in each pulmonary function measure. The adjusted mean (± standard error) percent change in each pulmonary function measure for each quintile of mean O_3 exposure was estimated by the least-squares means option of a general linear model program (PROC GLM; SAS Institute Inc., Cary, NC). The shape of the exposure–response function was also assessed by nonparametric smoothing with the locally weighted regression loess function (*11*) in S-plus (Statistical Sciences Division of Math Soft Inc., Seattle, WA). The significance of nonlinearities was tested with nonparametric *F* tests of generalized additive models (*12*).

Linear regressions were modeled by ordinary least squares estimation and by methods that accounted for the potential

intraclass correlation among hikers hiking on the same day (*13*). In addition, two linear regression models of the percent change in each of FEV_1, FVC, FEV_1/FVC, $FEF_{25-75\%}$, and PEFR as a function of mean O_3 exposure were assessed: one assuming a single slope relationship and a second assuming a piecewise relationship as a conservative approximation of nonlinearities suggested by the quintile and nonparametric analyses. For the piecewise models, an inflection point of 40 ppb mean O_3 was chosen on the basis of visual inspection of the results of the quintile and nonparametric analyses (Fig. 1). The piecewise model took the form

$$y = \alpha + \beta_1(x)(\delta) + \beta_2(x-40)(1-\delta), \quad (1)$$

where y = percentage change in each pulmonary function measure, x = each hiker's mean O_3 exposure, $\delta = 1$ if the mean O_3 exposure was <40 ppb, and $\delta = 0$ if the mean O_3 exposure was ≥40 ppb. An F statistic was calculated to test the difference between the two coefficients for O_3 in the piecewise models.

Logistic regression modeling was used to assess the relationship between pollution exposures and the odds of having a greater than 10% posthike decline in each measure of pulmonary function.

Results

Study population. The study recruitment protocol (see Methods) did not assess the total number of eligible hikers; as a consequence, overall participation rates are not available. Of the 766 hikers who volunteered to participate over the 1991–1992 study period, 595 (78%) provided acceptable and reproducible spirometry data both before and after the hike. Of the balance (n = 171), 120 (70%) hikers did not return for posthike spirometry, and the remainder did not meet acceptability (n = 45) or reproducibility (n = 6) criteria for spirometry (see Methods). Current smokers (n = 19), hikers with incomplete ambient O_3 data (n = 35), and hikers missing smoking status, respiratory disease histories, or other necessary covariates (n = 11) were excluded, leaving 530 hikers tested on 74 days for analysis. Of these hikers, 507 (96%) had measures of $PM_{2.5}$ and strong aerosol acidity concentrations available. For the remaining 23 hikers (4%), 15 (3%) hiked on days when $PM_{2.5}$ and strong aerosol acidity measurements were not taken and 8 (2%) hiked on a day when the available $PM_{2.5}$ and strong aerosol acidity measurements did not comply with quality assurance and quality control specifications. The majority of hikers in the analysis population were healthy, white (97%), male (71%) never smokers (76%) (Table 1). Ages ranged from 18 to 64 years, with a mean of 35 years.

Hikers excluded because of unacceptable or unreproducible spirometry, current smoking, or missing O_3 or other covariates were slightly younger. More hikers were excluded in 1992. Otherwise, hikers excluded from these analyses did not differ substantially from the analysis population (Table 1).

Air pollutant exposures. Peak O_3 levels at the mountain's summit were generally seen in early morning, with minimal hourly variation during midday (Fig. 2), a pattern seen at other high-altitude sites (*6,14*). The inverse of this diurnal pattern is typical at lower altitudes and in regions with significant local sources of O_3 pollution (*15*). As a result of daytime vertical mixing, O_3 levels at the mountain's summit and base were very similar during the usual hiking time of approximately 0900–1700 hours (Fig. 2). Hourly base and summit O_3 concentrations were available, on average, for 98% of hiking hours and ranged from 6 to 94 ppb. The average of the hourly O_3 concentrations during each hike ranged from 21 to 74 ppb with a mean ± standard deviation (SD) of 40 ± 12 ppb.

The median daily $PM_{2.5}$ concentration was 10 μg/m^3 with a maximum of 60 μg/m^3; the median strong aerosol acidity concentration was 0.3 μg/m^3 with a maximum of 20 μg/m^3. For most (89%) of the study days, strong aerosol acidity concentrations did not exceed 5 μg/m^3 (102 nmol/m^3).

Hikers' mean O_3 exposures were correlated with daytime $PM_{2.5}$ (Spearman r = 0.77) and strong aerosol acidity levels (Spearman r = 0.62). The Spearman partial correlation (adjusted for 24-hr mean O_3) between daytime $PM_{2.5}$ and strong aerosol acidity concentrations was 0.42.

Temperature. Summer temperatures on Mt. Washington are generally mild at the base and cool on the summit. The average temperature at the base during prehike and posthike spirometry was 19 ± 3°C (range 9–29°C). On test days, the average temperature was 17 ± 3°C (range 8–25°C) at the mountain's base and 8 ± 3°C (range -2–16°C) at the summit. Although peak hourly O_3 levels do not correspond to the hottest periods of the day at this site, average daily temperatures and mean 24-hr O_3 levels were positively correlated at both the summit (r = 0.69) and the base (r = 0.59).

Exercise. The average hiking time between the prehike and posthike spirometry was 8 ± 1.5 hr (range 2–12 hr). Most of the 530 hikers (75%) completed the 1,300-m climb to the summit of Mt. Washington, and 94% carried a backpack during the day's hike. For the 517 hikers with diary data, the mean self-reported maximum

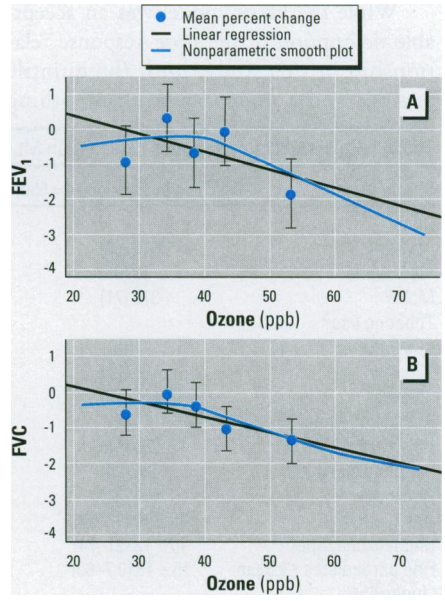

Figure 1. Posthike percentage changes in (A) forced expiratory volume in 1 sec (FEV_1) and (B) forced vital capacity (FVC) versus mean O_3 exposure after adjustment for age, hours hiked, sex, former versus never smoker, history of physician-diagnosed asthma or severe wheeze symptoms, carrying a backpack, reaching the summit, and mean ambient temperature during prehike and posthike spirometry. Error bars indicate 95% confidence intervals for mean percentage change in FEV_1 and FVC for each quintile of O_3. Quintile test for trend: p = 0.08 for FEV_1; p = 0.007 for FVC.

pulse rate attained during this exercise was 122 ± 26 beats/min or 66 ± 14% of age-predicted maximum pulse. Hikers varied widely in their usual activity levels, with self-reported aerobic exercise (a proxy measure of fitness) varying from 0 to over 50 hr/week, with a median of 6 hr/wk.

Pulmonary function and ozone. After adjustment for multiple covariates, linear models demonstrated a 2.6% decline in FEV_1 [95% confidence interval (CI), 0.4–4.7] and a 2.2% decline in FVC (CI, 0.8–3.5) for each 50-ppb increment in hikers' mean O_3 exposure (Table 2). Use of the maximum rather than the mean (see Methods) acceptable and reproducible values for each pulmonary function measure did not change the results. These models did not include adjustment for the intraclass correlation among hikers hiking on the same day because these values were quite small (<5%) and nonsignificant. Adjustment for $PM_{2.5}$ and strong aerosol acidity concentrations did not change the observed inverse relationship between changes in FEV_1 and hikers' mean O_3 exposures, but this association was no longer significant (Table 2). The inverse association between ambient O_3 and changes in FVC was diminished and nonsignificant after adjustment for the other pollutants (Table 2).

While the linear model was an acceptable description of the dose–response relationship in this study, both the quintile analysis and a nonparametric smoothing function suggested nonlinearity in the relationship between posthike percentage changes in FEV_1 and FVC and hikers' mean O_3 exposures, with the steepest changes occurring at mean O_3 exposures above approximately 40 ppb (Fig. 1). These deviations from linearity were not significant at the $p = 0.05$ level in generalized additive models ($p = 0.07$ for FEV_1; $p = 0.08$ for FVC). In adjusted piecewise models, there was a significant difference between the estimated effect of O_3 above and below 40 ppb ($p = 0.005$ for FEV_1; $p = 0.001$ for FVC). Above 40 ppb, there was a 4.4% decline in FEV_1 (CI, 0.5–8.2) and a 3.2% decline in FVC (CI, 0.7–5.6) for each 50-ppb increment of mean O_3 exposure (Table 2). These inverse relationships above 40 ppb mean O_3, although no longer significant, did not change substantially after adjustment for ambient $PM_{2.5}$ and aerosol acidity concentrations (Table 2).

Table 1. Selected characteristics of hikers on Mt. Washington, New Hampshire, 1991–1992

Characteristic	Analysis population ($n = 530$)	Excluded hikers ($n = 116$)[a]	One-way hikers ($n = 120$)[a]
Race[b]			
White	510 (97)	110 (96)	NA
Nonwhite	18 (3)	4 (4)	
Male[b]	375 (71)	81 (70)	71 (66)
Tobacco use[b]			
Current	0 (0)	21 (19)	NA
Former	125 (24)	8 (7)	
Never	405 (76)	80 (73)	
Asthma or wheeze[b]	40 (8)	11 (10)	NA
Hiked in 1992[b]	290 (55)	84* (72)	74 (62)
Reached summit[b]	396 (75)	82 (73)	NA
Backpack[b]	498 (94)	102 (93)	NA
Age (years)[c]	35 ± 10 (18–64)	32 ± 10** (18–65)	35 ± 11 (18–64)
Mean ozone (ppb)[c,d]	40 ± 12 (21–74)	39 ± 10 (21–71)	41 ± 12 (23–74)
Fine particulates ≤2.5 μm ($\mu g/m^3$)[c,e]	15 ± 13 (0.7–60)	14 ± 9 (0.7–60)	15 ± 12 (0.7–60)
Aerosol acidity, H_2SO_4 equivalent($\mu g/m^3$)[c,e]	2 ± 4 (-0.1[f]–20)	2 ± 3 (0–20)	2 ± 3 (-0.1[f]–15)
Mean temperature base + summit (°C)[c]	12 ± 3 (5–20)	12 ± 3 (8–20)	13 ± 3 (5–20)
Baseline FEV_1 (ml)[c]	4,083 ± 815 (1,825–6,561)	4,212 ± 750 (2,418–5,820)	4,125 ± 867 (2,284–6,400)
Baseline FVC (ml)[c]	5,135 ± 1,024 (2,886–7,972)	5,175 ± 951 (2,765–7,134)	5,121 ± 1,006 (2,755–7,332)
Hours hiked[c]	8 ± 1.5 (2–12)	8 ± 1.5 (1–11)	NA

Abbreviations: NA, not available; SD, standard deviation; FEV_1, forced expiratory volume in 1 sec; FVC, forced vital capavity.

[a]Total numbers for each variable vary because of missing data; one-way hikers did not return for posthike spirometry.

[b]Values shown are number (%).

[c]Values shown are mean ± SD (range).

[d]Where hiker-specific mean O_3 values were not available, 8-hr (0900–1700 hours) mean O_3 values were used.

[e]From a 10-hr daytime sample collected at the base monitoring site; reported concentrations are adjusted to standard temperature and pressure.

[f]Negative values for acid aerosol levels are possible in cases where the acid concentration is very close to zero or there is an excess of basic compounds in the aerosol.

*$p<0.001$ by chi-square comparison with the analysis population.

**$p<0.01$ by two-sided t-test comparison of means with the analysis population.

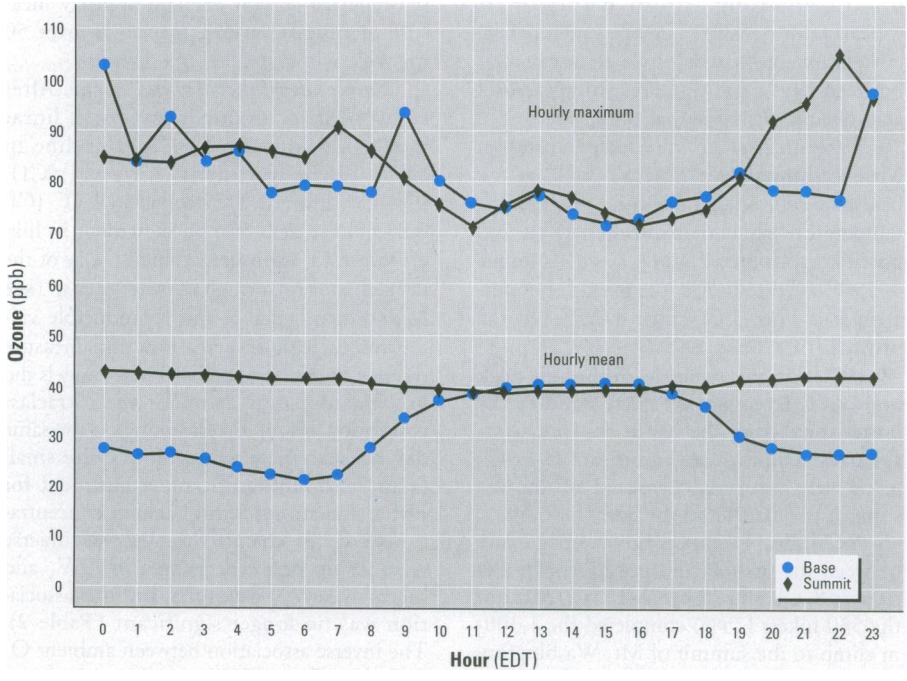

Figure 2. Maximum and mean hourly ozone levels (ppb) at the summit and base of Mt. Washington for 74 days on which study hikers were evaluated in summer 1991 and 1992. EDT, Eastern Daylight Savings Time.

Hikers with a self-reported history of physician-diagnosed asthma or severe wheeze symptoms over the previous year had significantly greater O_3-associated decrements in FEV_1 (7.5% decline for each 50-ppb increment in O_3) than other hikers (1.8% decline for each 50-ppb increment in O_3) (Table 3). Adjustment for ambient $PM_{2.5}$ and aerosol acidity concentrations did not change the magnitude or significance of this difference. Male hikers had greater O_3-related FEV_1 and FVC declines than female hikers; never smokers had greater O_3-related FVC declines than former smokers; and longer hikes were associated with greater O_3-related FEV_1 and FVC declines than shorter hikes, although none of these differences was significant (Table 3). There was no association between O_3 responsiveness and age (Table 3).

There were insufficient numbers of hikers with greater than 10% declines in FEV_1 ($n = 11$), FVC ($n = 8$), and FEV_1/FVC ($n = 4$) to evaluate this group separately. However, 109 and 71 hikers had greater than 10% posthike declines in $FEF_{25–75\%}$ and PEFR, respectively. After adjustment for multiple covariates, O_3 was significantly associated with greater than 10% declines in $FEF_{25–75\%}$ [odds ratio (OR) = 3.67; CI, 1.25–10.78; $p = 0.02$ for each 50-ppb increase in mean O_3].

Pulmonary function and fine particulate matter and aerosol acidity. There were consistent associations between ambient $PM_{2.5}$ exposures and changes in FVC (0.4% declines; CI, 0.2–0.6 across the interquartile range for $PM_{2.5}$ concentration of 9 $\mu g/m^3$) and PEFR (0.8% declines; CI, 0.01–1.6 across the interquartile range for $PM_{2.5}$) that persisted but were nonsignificant after adjustment for ambient O_3 (Table 4). Changes in PEFR had the largest inverse association with strong aerosol acidity exposures (0.4% decline; CI, 0.1–0.7 declines across the interquartile range for aerosol acidity of 1.3 $\mu g/m^3$ or

Table 2. Linear regression models of the percentage change in pulmonary function as a function of ambient ozone[a]

Model (n = 530)	Percent change FEV_1	Percent change FVC	Percent change PEFR	Percent change FEV_1/FVC	Percent change $FEF_{25-75\%}$
Univariate	-0.045 ± 0.018 (p = 0.01)	-0.040 ± 0.012 (p = 0.0006)	-0.033 ± 0.047 (p = 0.48)	-0.005 ± 0.015 (p = 0.72)	-0.005 ± 0.057 (p = 0.93)
Adjusted[b]	-0.051 ± 0.022 (p = 0.02)	-0.043 ± 0.014 (p = 0.003)	-0.018 ± 0.058 (p = 0.76)	-0.009 ± 0.018 (p = 0.61)	-0.027 ± 0.070 (p = 0.70)
Adjusted[c] + $PM_{2.5}$ + acidity	-0.048 ± 0.032 (p = 0.13)	-0.023 ± 0.023 (p = 0.32)	-0.049 ± 0.074 (p = 0.51)	-0.027 ± 0.023 (p = 0.24)	-0.042 ± 0.107 (p = 0.69)
Adjusted[b] (≥40 ppb[d])	-0.087 ± 0.039 (p = 0.03)	-0.063 ± 0.025 (p = 0.01)	-0.082 ± 0.103 (p = 0.42)	-0.026 ± 0.032 (p = 0.42)	-0.113 ± 0.124 (p = 0.36)
Adjusted[c] + $PM_{2.5}$ + acidity (≥40 ppb[d])	-0.094 ± 0.050 (p = 0.06)	-0.048 ± 0.036 (p = 0.18)	-0.178 ± 0.118 (p = 0.13)	-0.049 ± 0.037 (p = 0.18)	-0.177 ± 0.170 (p = 0.30)

Abbreviations: FEV_1, forced expiratory volume in 1 sec; FVC, forced vital capacity; PEFR, peak expiratory rate; $FEF_{25-75\%}$, forced expiratory flow between 25 and 75% of FVC; $PM_{2.5}$, fine particulate matter.

[a]Regression coefficients for O_3 ± standard error in posthike percent change per ppb mean O_3 for each pulmonary function measure.

[b]Adjusted for age, hours hiked, sex, former versus never smoker status, history of physician-diagnosed asthma or severe wheeze symptoms over previous year, carrying a backpack, reaching the summit, and mean ambient temperature during prehike and posthike spirometry.

[c]Adjusted as above + ambient fine particulate (≤2.5 μm or $PM_{2.5}$) + ambient strong aerosol acidity concentrations; because of missing fine particulate and/or strong aerosol acidity values, 507 observations were included in these adjusted models.

[d]Regression coefficients of piecewise model above inflection point of 40 ppb O_3.

26.5 nmol/m^3). This association persisted (but was not statistically significant) after adjustment for mean O_3 (Table 4). Although there were associations between posthike changes in FEV_1 and both $PM_{2.5}$ (0.4% decline across the interquartile range of 9 μg/m^3) and aerosol acidity (0.1% decline across the interquartile range of 1.3 μg/m^3) exposures, these associations were diminished and no longer significant after adjustment for O_3 (Table 4). Changes in the other measures of pulmonary function (FEV_1/FVC and $FEF_{25-75\%}$) had no consistent or significant associations with ambient $PM_{2.5}$ or strong aerosol acidity. These effect estimates were of similar magnitude to the estimated O_3 effect. For example, in multivariate models, each 15-ppb increase in mean O_3 (the interquartile range of mean O_3 exposures) was associated with a 0.8% decline in FEV_1 and a 0.6% decline in FVC (Table 2).

Discussion

We assessed the effects of simultaneous exposures to ambient O_3, $PM_{2.5}$, and strong aerosol acidity on pulmonary function in an adult population with broad ranging ages and fitness levels; this has not been done in most other field studies of adult O_3 exposure (*16–18*), despite the fact that exposure to pollutant mixtures is characteristic of the ambient environment, which in turn affects diverse populations. The same magnitude of O_3-associated declines in FEV_1 was seen after simultaneous adjustment for $PM_{2.5}$ and acid aerosols (Table 2). There were consistent, albeit diminished, O_3-associated declines in FVC after adjustment for other ambient pollutant exposures (Table 2).

Based on the average ambient O_3 during exercise, the estimated effects of O_3 exposure were larger than have been described in most previous field studies (*16–18*) and experimental chamber studies (*1,3*). Among the Mt. Washington hikers with mean FEV_1 of 4.08 liters and mean FVC of 5.14 liters, our findings approximate declines of 106 ml and 113 ml, respectively, in each of these measures for each 50-ppb increment in mean ambient O_3 level. When restricted to mean O_3 exposures ≥40 ppb, our effect estimates were even larger (Table 2). In a study of 24 male and female joggers by Selwyn et al. (*16*), results were consistent with a smaller effect estimate of 20-ml decline in FEV_1 for each 50-ppb increment in O_3. Our results are closer to those of Brunekreef et al. (*17*) in their study of 23 male amateur cyclists and those of Spektor et al. (*18*) in a study of 30 exercising adults; their effect estimates were consistent, respectively, with 78- and 70-ml declines in FEV_1 and 111- and 105-ml declines in FVC for each 50-ppb increment in mean O_3 concentration during exercise. Differences in dose–response modeling are unlikely to explain differences in effect estimates among field studies. Previous field studies (*16–18*) also used a linear dose response as the best description of the ozone–pulmonary function relationship and were conducted at ambient O_3 concentrations similar to those observed on Mt. Washington.

Differences in exposure duration may explain the greater mean O_3 effect estimates seen in the current study. In three previous field studies (*16–18*), most subjects' exercise periods were less than 2 hr, compared with an average exercise period of 8 hr on Mt.

Table 3. Linear regression models of the percentage change in pulmonary function as a function of mean ozone by respiratory disease history, smoking status, sex, age, and hours hiked[a]

Variable	Percent change FEV_1	Percent change FVC
Respiratory disease history		
Asthma or wheeze (n = 40)	-0.149 ± 0.054 (p = 0.04)[b]	-0.069 ± 0.035 (p = 0.40)[b]
Other hikers (n = 490)	-0.036 ± 0.024	-0.039 ± 0.015
Smoking		
Former (n = 125)	-0.024 ± 0.040 (p = 0.42)[b]	-0.004 ± 0.026 (p = 0.07)[b]
Never (n = 405)	-0.059 ± 0.025	-0.055 ± 0.016
Sex		
Male (n = 375)	-0.055 ± 0.025 (p = 0.70)[b]	-0.051 ± 0.016 (p = 0.24)[b]
Female (n = 155)	-0.039 ± 0.039	-0.019 ± 0.025
Age (years)		
18–27 (n = 135)	-0.043 ± 0.027 (p = 0.89)[c]	-0.038 ± 0.017 (p = 0.67)[c]
28–37 (n = 185)	-0.067 ± 0.024 (p = 0.33)[c]	-0.046 ± 0.016 (p = 0.92)[c]
38–47 (n = 142)	-0.053 ± 0.026 (p = 0.48)[c]	-0.039 ± 0.017 (p = 0.52)[c]
48–64 (n = 68)	-0.038 ± 0.033	-0.048 ± 0.021
Hours hiked		
8–12 (n = 265)	-0.069 ± 0.029 (p = 0.32[b])	-0.056 ± 0.019 (p = 0.25)[b]
2–8 (n = 265)	-0.033 ± 0.029	-0.029 ± 0.018

Abbreviations: FEV_1, forced expiratory volume in 1 sec; FVC, forced vital capacity.

[a]Regression coefficients for O_3 ± standard error in posthike percent change per ppb mean O_3 adjusted for age, hours hiked, sex, former versus never smoker status, history of physician-diagnosed asthma or severe wheeze symptoms over previous year, carrying a backpack, reaching the summit, and mean ambient temperature during prehike and posthike spirometry.

[b]p-Values for difference in O_3 effect between groups.

[c]p-Values for difference in O_3 effect between each age category and the oldest age group.

Table 4. Linear regression models of the percentage change in pulmonary function as a function of ambient pollution for fine particulate matter ($n = 507$) and aerosol acidity ($n = 507$)[a]

Parameter/Model	Percent change FEV_1	Percent change FVC	Percent change PEFR
Fine particulate matter (≤2.5 μm, μg/m³)			
Univariate	-0.035 ± 0.015 ($p = 0.02$)	-0.038 ± 0.011 ($p = 0.0004$)	-0.084 ± 0.035 ($p = 0.02$)
Adjusted[b]	-0.041 ± 0.018 ($p = 0.03$)	-0.043 ± 0.013 ($p = 0.001$)	-0.087 ± 0.044 ($p = 0.05$)
Adjusted[c] + O_3	-0.015 ± 0.026 ($p = 0.56$)	-0.029 ± 0.018 ($p = 0.11$)	-0.074 ± 0.060 ($p = 0.22$)
Aerosol acidity (sulfuric acid equivalent, μg/m³)			
Univariate	-0.100 ± 0.050 ($p = 0.05$)	-0.106 ± 0.036 ($p = 0.003$)	-0.300 ± 0.117 ($p = 0.01$)
Adjusted[b]	-0.109 ± 0.054 ($p = 0.05$)	-0.107 ± 0.039 ($p = 0.006$)	-0.294 ± 0.128 ($p = 0.02$)
Adjusted[c] + O_3	-0.047 ± 0.064 ($p = 0.47$)	-0.062 ± 0.046 ($p = 0.18$)	-0.258 ± 0.152 ($p = 0.09$)

Abbreviations: FEV_1, forced expiratory volume in 1 sec; FVC, forced vital capacity; PEFR, peak expiratory rate.
[a]Regression coefficients for each pollutant ± standard error in posthike percent change per μg/m³ where fine particulate matter and strong aerosol acidity concentrations are adjusted to standard temperature and pressure.
[b]Adjusted for age, hours hiked, sex, former versus never smoker status, history of physician-diagnosed asthma or severe wheeze symptoms over previous year, carrying a backpack, reaching the summit, and mean ambient temperature during prehike and posthike spirometry.
[c]Adjusted as above + mean ambient O_3.

Washington. On Mt. Washington, the number of hours hiked was an independent predictor of declines in measures of pulmonary function for FEV_1 and FVC [after adjustment for O_3, each hour hiked was associated with a 0.3% decline ($p = 0.05$) in FEV_1; data not shown]. In addition, longer hikes were associated with a greater mean O_3 effect (Table 3).

Although other factors contributing to the effects of O_3 exposure—minute ventilation, O_3 concentration pattern, and participants' ages, for example—may have increased or decreased the effect of mean O_3 exposure in this setting compared with other studies, estimates of each hiker's minute ventilation were not available. Proxy measures of hike work—reaching the mountain summit, carrying a backpack, maximum self-reported pulse, or percentage of age-predicted maximum pulse—were not significant independent determinants of decrements in pulmonary function, and the interaction between each of these measures and mean O_3 were not significant (data not shown). In addition, there was minimal hourly O_3 variation during hiking periods (Fig. 1), a circumstance that likely attenuates rather than enhances mean O_3 effects (*19*). Lastly, the hikers were, on average, older than participants in other field (*17,18*) and chamber studies of O_3 exposure (*1–3*), a characteristic associated with decreased O_3 responsiveness in other studies (*20*) but not here (Table 3).

Although we did not collect information on nonparticipating eligible hikers, it is unlikely that selection bias influenced the results because hikers' willingness to participate is very unlikely to have been related either to air pollutant levels or their responsiveness to pollutants. It is possible that unrecognized confounding influenced our results. However, the observed associations were adjusted for exposure to important potential confounders of the O_3–pulmonary function relationship: concomitant pollutants and temperature. Humidity information was not available for these analyses, but, given the diurnal O_3 pattern (Fig. 1) and moderate-to-cool temperatures characteristic of the site, humidity is unlikely to have been an important confounder. In addition, positive confounding by exercise or exercise-induced asthma is unlikely to have occurred for several reasons. First, hikers with a history of asthma or severe wheeze symptoms over the previous year were no more likely than healthy hikers to hike on more polluted days (e.g., on days with O_3 concentrations above the median, 6% of hikers had a history of asthma or wheeze compared to 9% of hikers who hiked when O_3 concentrations were below the median; $p = 0.19$, data not shown). Second, the same work or exercise was performed by most participants; adjustment for the hours hiked, reaching the mountain summit, carrying a backpack, maximum self-reported pulse, or percentage of age-predicted maximum pulse did not change the estimated pollution effects (data not shown).

In general, O_3-associated changes in pulmonary function are greater in natural than in controlled exposure settings (*18*). Although synergism or interaction among a variety of uncontrolled environmental factors have been hypothesized to play a role in this finding, the explanation for this discrepancy is unknown. As a consequence, there is ongoing controversy regarding the appropriate exposure–response relationship for O_3-associated pulmonary function changes. Our findings provide additional support for increased effect estimates under conditions of naturally occurring O_3 exposure, particularly under prolonged exposure conditions such as hiking, and even after adjustment for concurrent environmental exposures ($PM_{2.5}$, acid aerosols, and temperature).

Exposures to both particulate (*21,22*) and strong aerosol acidity (*23,24*) pollutants have been independently associated with acute decrements in pulmonary function. As was the case for O_3, the observed associations between measures of pulmonary function and exposures to ambient $PM_{2.5}$ and aerosol acidity were larger than observations from other field studies (*22,23*). Furthermore, there were consistent effects of ambient $PM_{2.5}$ on both FVC and PEFR and of ambient aerosol acidity on PEFR after adjustment for O_3 (Table 4). Dockery and Pope (*22*) estimated a 0.15% decrease in FEV_1 (they did not report FVC results) and a 0.08% decline in PEFR for each 10 μg/m³ increase in inhalable particulate matter (aerodynamic diameter ≤10 μm) in an analysis combining results from several studies of school children. Assuming that 6 μg/m³ of $PM_{2.5}$ corresponds to 10 μg/m³ of inhalable particulate matter (*22*), our results are consistent with a greater effect estimate—a 0.25% decrease in FEV_1 and a 0.52% decline in PEFR after adjustment for multiple covariates (Table 4). At the same $PM_{2.5}$ concentrations and after additional adjustment for O_3, the observed declines in FEV_1 and PEFR persist, but are nonsignificant and diminish to 0.09% and 0.44%, respectively (Table 4).

For each 6 μg/m³ (125 nmol/m³) increment in acid aerosol exposure, our results include a 1.8% decline in PEFR (or 1.5% decline after adjustment for O_3) (Table 4), a larger effect estimate than the 0.4–0.8% decrements described elsewhere, with a similar exposure in children (*23*).

Despite our relatively large effect estimates, the mean changes in pulmonary function in this setting were small and unlikely to result in clinical symptoms in most individuals. However, there is a wide range of individual susceptibility to pollutants (*25,26*). Susceptible individuals are likely to have substantial declines in pulmonary function that are not apparent in an assessment of population means. As a result, a relatively minor change in the overall mean effect of exposure (as reported here) may still result in substantial changes for certain sensitive subgroups. For example, several studies support increased O_3 susceptibility among asthmatics demonstrated by

greater lung function response (*25,27*) or enhanced pulmonary inflammatory response (*28*). Hikers with a history of physician-diagnosed asthma or severe wheeze were a sensitive subgroup in these analyses, with a fourfold greater responsiveness to O_3 than other hikers (Table 3). This finding of increased susceptibility to O_3 was not affected by adjustment for concomitant pollutant exposures or exercise. In addition, because asthmatics taking medication may be less sensitive to O_3, we are likely to have underestimated the maximum increased sensitivity of this subgroup because we lacked information regarding effect modification by medication. Lastly, our results demonstrated that a substantially increased fraction of the exercising population had significant declines in lung function (>10% declines in $FEF_{25-75\%}$, for example) on days with higher O_3.

We observed significant effects of mean ambient O_3, $PM_{2.5}$, and strong aerosol acidity on pulmonary function in a wilderness area designated for air quality protection (*6*). Large numbers of visitors engage in prolonged outdoor exercise in this area and are thereby at risk for acute health effects related to ambient pollution exposures. Even without considering differences in individual susceptibility, the observed effect estimates are notable for having occurred among hikers exposed to hourly O_3 concentrations averaging 40 ppb, a relatively low level characteristic of much of the continental United States and well below the currently operant National Ambient Air Quality Standard of 0.12 ppm (120–124 ppb) for hourly O_3. Furthermore, this is the first epidemiologic study to report the effects of long-term ambient O_3 exposures, which are applicable to recent revisions to the O_3 standard that are based on an 8-hr average 0.08-ppm (80–84 ppb) exposure limit (*29*). Physicians, public health officials, and the general public should be aware of the potential acute health impact of relatively low-level air pollutants not only among residents of urban and industrial regions but also among individuals engaged in outdoor recreation in certain wilderness areas.

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